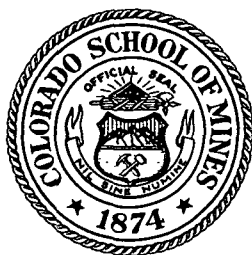


W73-32279



REMOTE SENSING AIDS GEOLOGIC MAPPING

by

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ON

REMOTE SENSING OF ENVIRONMENT

Remote Sensing Report 72-8

NASA Grant NGL 06-001-015
National Aeronautics and Space Administration
Office of University Affairs
Washington, D.C. 20546

October 1972

REMOTE SENSING PROJECTS

DEPARTMENT OF GEOLOGY

COLORADO SCHOOL OF MINES ♦ GOLDEN, COLORADO

REMOTE SENSING AIDS GEOLOGIC MAPPING

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ABSTRACT

Remote sensing techniques have been applied to general geologic mapping along the Rio Grande rift zone in central Colorado. A geologic map of about 1,100 square miles was prepared utilizing 1) prior published and unpublished maps, 2) detailed and reconnaissance field maps made for this study, and 3) remote sensor data interpretations. The map is to be used for interpretation of the complex Cenozoic tectonic and geomorphic histories of the area.

Regional and local geologic mapping can be aided by the proper application of remote sensing techniques. Conventional color and color infrared photos contain a large amount of easily-extractable general geologic information and are easily used by geologists untrained in the field of remote sensing. Other kinds of sensor data used in this study, with the exception of SLAR imagery, were generally found to be impractical or inappropriate for broad-scale general geologic mapping; these data can, however, be effectively applied to specific problems in relatively small areas, but some knowledge of the principles of remote sensing is necessary for the acquisition of the proper data and for subsequent interpretation.

INTRODUCTION

A variety of remote sensor data has aided geologic mapping in central Colorado. This paper summarizes the application of sensor data to both regional and local geologic mapping and presents some conclusions on the practical use of remote sensing for solving geologic mapping problems. It is emphasized that this study was not conducted primarily to test or evaluate remote sensing systems or data, but, rather, to apply sensor data as an accessory tool for geologic mapping. All conclusions reached on the utility of the various sensor data and interpretation techniques for geologic mapping are by-products of attempts to use them.

The remote sensor data used in this study were acquired by the NASA Earth Observations Aircraft Program for the Bonanza remote sensing project (NASA Grant NGL 06-001-015) at the Colorado School of Mines. The type and quality of the data, therefore, are defined by the systems aboard the various NASA aircraft.

THE AREA

No consideration was given to the particular "suitability" of the area for the application of remote sensing techniques. The area was chosen solely for its critical importance to the understanding of Cenozoic tectonic and geomorphic evolution in central Colorado. Consequently, the area deviates markedly from the concept of a geologic remote sensing "test site"--an area characterized by its structural simplicity, highly contrasting rock types, excellent exposures, and easy access.

The area is centered along the Rio Grande rift zone, a major tectonic element of late Tertiary age, extending from southern New Mexico for some 600 miles northward into northern Colorado (Fig. 1). Within the study area the geology is complex

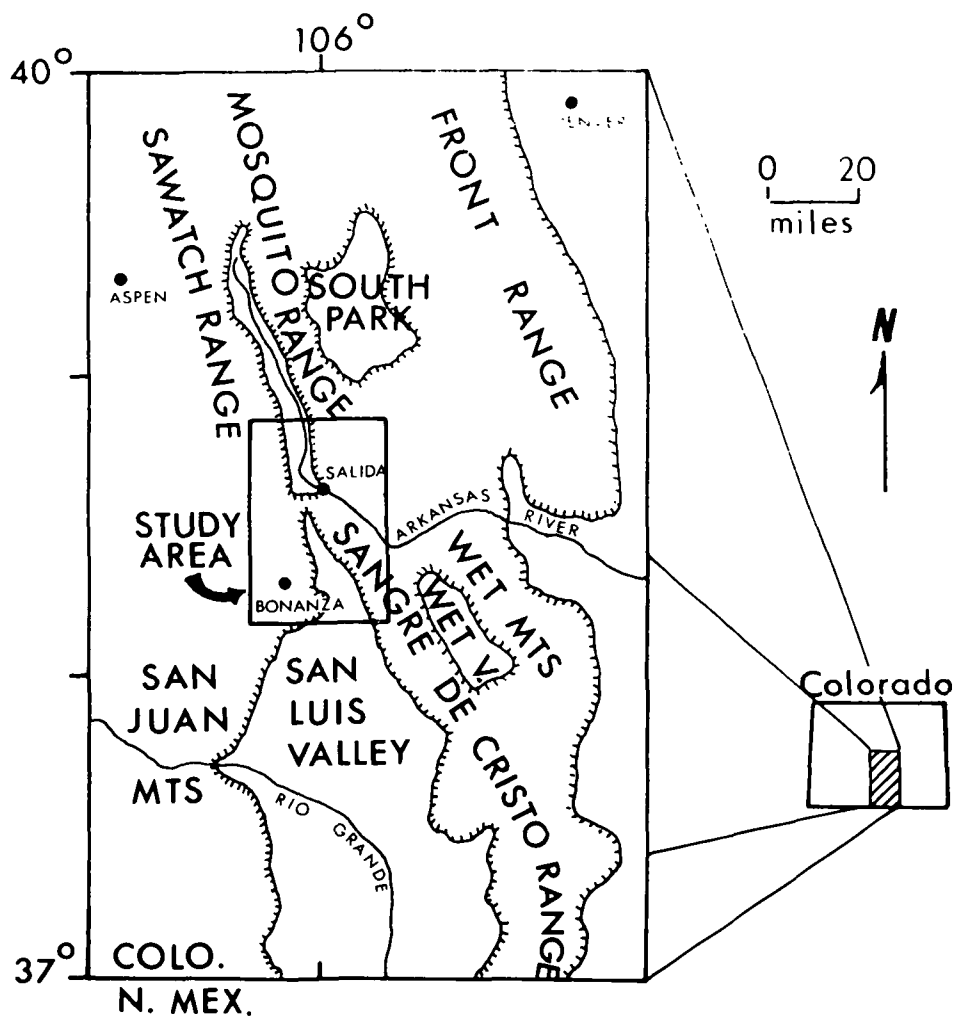


FIGURE 1. INDEX MAP OF STUDY AREA. Internal portion of Rio Grande rift zone extends northward from the northern San Luis Valley into Arkansas River Valley.

and diverse. The structurally and topographically low San Luis and Arkansas valleys follow the internal portion of the rift zone. The valleys are filled with upper Tertiary clastic sediments shed from the bordering uplifts. The mountain ranges on the west and east are composed of Precambrian igneous and metamorphic rocks, complexly deformed Paleozoic sedimentary rocks, and Tertiary igneous plutons. Oligocene volcanic rocks of the Bonanza volcanic field form the mountains in the southwestern part of the area.

Dense conifer forests and extensive alluvial and colluvial deposits cause constant problems in bedrock geologic mapping, both in the field and by the use of remote sensor data. Relief between valley floors and adjacent mountain peaks is commonly 4,000 feet, locally reaching as much as 7,000 feet. Vehicular travel is impossible in most of the rugged mountain terrain.

THE STUDY

A primary element of this study has been the preparation of a geologic map covering about 1,100 square miles, that could be used to interpret the complex tectonic and geomorphic history of this portion of the Rio Grande rift zone. Numerous structurally- and lithologically-controlled mineral deposits provided additional incentive for studying the structure, location, and distribution of the rocks and sediments of this area.

In many respects, our study has been similar to "standard" geologic mapping programs in which conventional air photos are used as a mapping tool; it differed, however, by its broader areal scope and wider use of remote sensor data. Effective application of remote sensing was critical because of the limited time available to complete the task.

The study started with library research and the compilation of previous geologic mapping within and bordering the area (Fig. 2). A map scale of 1:62,500 was chosen to accommodate the necessary detail while maintaining a workable size. From the remaining unmapped area, several subareas were selected for detailed and reconnaissance field mapping. Selection of these subareas was based on the following considerations: 1) projection of major structural trends from previous mapping, 2) geologic analysis of small-scale color and color infrared (IR) photographs (1:100,000), and 3) isolation from previously mapped areas. Detailed studies of local areas within the study region provided an opportunity to accumulate a working knowledge of how the various lithologic, structural, and geomorphic features were expressed on the sensor data and develop efficient interpretive methods and techniques. Concurrent detailed mapping by other investigators yielded additional ground data as the study progressed.

The areas mapped in the field provided a network of ground control scattered throughout the study area. Mapping the intervening areas was accomplished by geologic interpretation of a variety of remote sensor data, supplemented by frequent field checks. Special enhancement and processing techniques were applied to selected pieces of sensor data in an attempt to decrease interpretation time (expense) and extract added geologic information.

Geologic features (faults, fractures, contacts, fold axes) were traced on clear acetate overlays and final interpretations were transferred to 1:62,500 topographic base maps, a separate map being used for each type of sensor data. A preliminary geologic map of the entire study area was made by compiling all the geologic mapping data, including previous and current field mapping and remote sensor data interpretations, on a 1:62,500 topographic base map. Field checks were made in selected areas, particularly where structural interpretation or lithologic identification was questionable or conflicting. A final geologic map was constructed including appropriate modifications.

SENSOR DATA

NASA missions 101, 105, 168, and 184 provided a variety of remote sensor data over the study area (4,5,6,7,8). High-altitude color and color infrared (IR) photographic coverage (1:100,000) is nearly complete. Low-altitude color and color IR photography at scales ranging between 1:12,000 and 1:24,000 was obtained over nearly 80 percent of the area.

Four-band multiband photography (both high- and low-altitude) and daytime and pre-dawn thermal IR imagery (3-5 μ m and 8-14 μ m) were flown in selected areas. Brute-force and synthetic-aperture side-looking airborne radar (SLAR) at various polarization combinations was acquired over a large part of the area, and low sun-angle photography (LSAP) was obtained in the northeastern and eastern parts of the area. Thermal IR spectrometric, microwave radiometric, and radar scatterometric data were acquired on a few lines, but these data have had no application to this investigation. Ground control data were gathered during each mission to aid in the interpretation process.

SENSOR DATA APPLICATIONS

Photographic data were used extensively in the geologic mapping. High-altitude color and color IR photography (1:100,000) was extremely useful in placing local areas into proper regional geologic and geographic perspective. Its primary use,

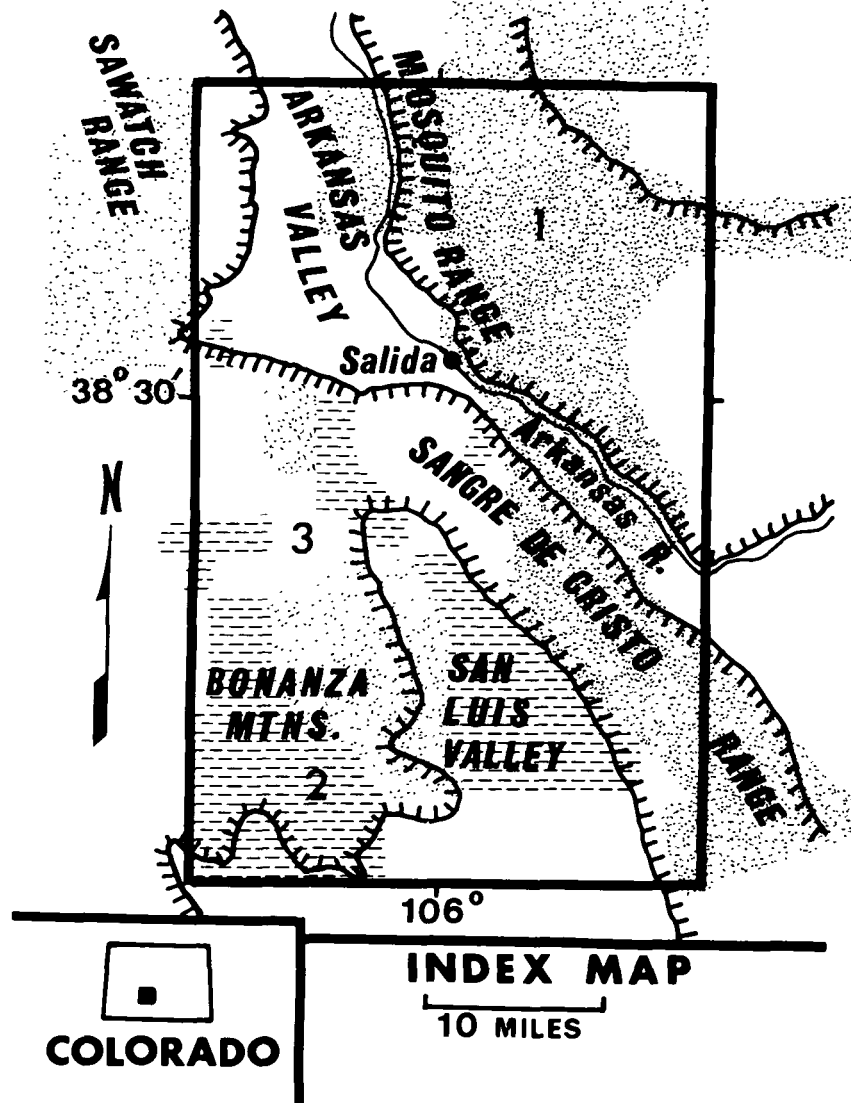


FIGURE 2. INDEX OF GEOLOGIC MAPPING. 1 (stipple) are areas covered by prior published and unpublished maps; 2 (dash) are field areas mapped in detail or reconnaissance during this study; 3 (open) are areas mapped from remote sensor data supplemented by field checks.

however, was for delineating and tracing regional structural features and locating potential problem areas.

Low-altitude color and color IR photography (1:12,000 to 1:24,000) was the primary mapping tool. The low-altitude photography was used both in the field as an aid in detailed and reconnaissance mapping and also in the laboratory to map details of local geologic features identified on high-altitude (small scale) photography. Low-altitude photography was invaluable in extending geologic mapping from geologically known into unknown areas in the detail necessary for this study, and in further restricting problematical areas for subsequent field visitation.

The southwestern portion of the Bonanza volcanic field was divided into three test areas in order to determine the best technique for applying large-scale color and color IR photography and thermal IR imagery to local detailed mapping problems. In the first area, the photography and imagery were used to refine prior field mapping. In the second area, the photos were used in the field as a mapping base. In the third area, the photos and imagery were used to construct a photo-geologic map prior to field studies and subsequently during field mapping. The technique used in the third area produced the best results in the shortest period of time. During photo-geologic mapping 75 percent of all faults were located, and 93 percent of all Quaternary deposits and 62 percent of the areas containing one of six Tertiary volcanic units were correctly identified--all prior to going to the field.

Low sun-angle photography (B/W IR, with W 25 filter) proved extremely useful for mapping the distribution of nine levels of Quaternary pediment and stream terrace gravel in the Arkansas River Valley (Fig. 3). The gravel surfaces are defined



FIGURE 3. LOW SUN-ANGLE PHOTOGRAPHY (LSAP).
Shadowing produced by low sun-angle illumination helps to delineate gravel-capped surfaces (S).

by their height above modern stream base and above each other; shadowing produced by low sun-angles enhanced the topographic differences making surface detection and mapping easier and faster than with conventional high sun-angle photography. In addition, a relatively large photographic scale (1:24,000) and moderate sun-angle (24° - 27°) increased the utility of the LSAP for mapping textural differences between surface materials. However, the large scale and moderate sun-angle decreased the utility of the LSAP for structural studies because, 1) subtle, topographically-expressed structures were disguised in a maze of detail; and 2) only small segments of major structural features were imaged in a single photograph making recognition and identification difficult.

High-altitude multiband photography was examined in several areas. An extremely small scale, combined with over-all poor photo quality (overexposure) rendered the high-altitude multiband photography inadequate for this investigation.

Low-altitude multiband photography was examined in several areas of known geology to determine whether it contained a significant amount of geologic information over and above the information extracted from simultaneously-obtained color and color IR photography. Each of the four bands (standard blue, green, red and red film/filter combinations) of photography was studied by conventional photographic techniques, using stereoscopic analysis where possible. In general, the "new information" content of the multiband photography was very low and interpretation time quite long. Consequently, multiband photography was considered impractical for this investigation.

Thermal IR scanner imagery (8-14 μ m and 3-5 μ m), obtained over areas of known geology during pre-dawn and daytime flights, was analyzed. Some new geologic information not previously discovered during field mapping or photo interpretation was extracted from the imagery, but the information was of minor consequence to the mapping program. In general, the inability to recognize and interpret known geologic features with certainty, coupled with the relatively poor spacial resolution, inherent image distortion, and non-stereo-viewing characteristics of the data, made use of the thermal IR imagery in geologically-unknown areas tenuous. Thermal IR imagery is not considered a routine geologic mapping tool in this area.

SLAR imagery has thus far been sparingly used. The imagery is generally poor quality (low resolution, flat contrast, frequent image disruption) and does not justly represent the potential of SLAR imagery for regional structural analysis. Analysis of a few fair-quality images (Fig. 4) suggests that good quality, high-resolution

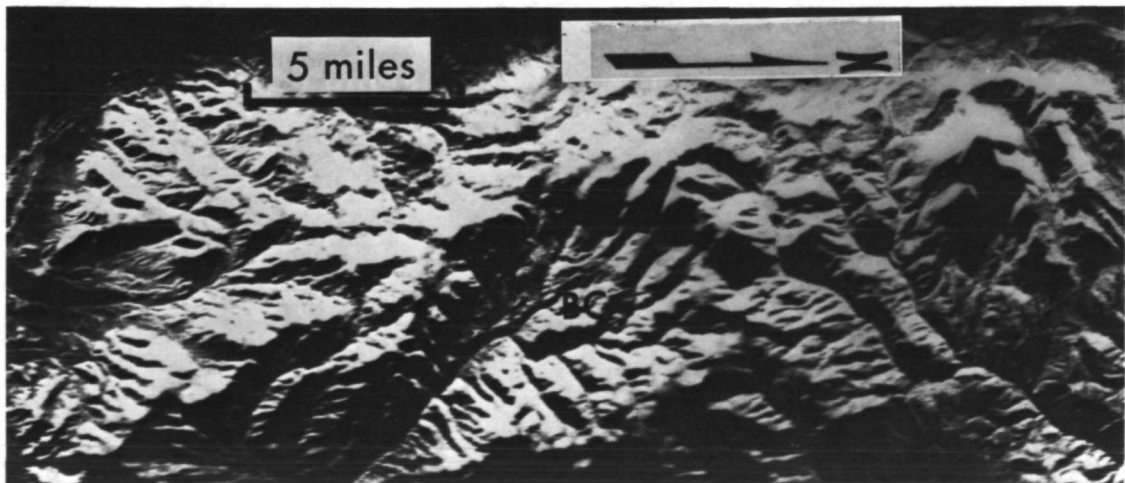


FIGURE 4. DPD-2 SLAR IMAGERY, Brute-force, VH imagery of the Bonanza caldera (BC) in the Bonanza volcanic field.

SLAR imagery of the entire area would have aided in delineating and mapping major topographically-expressed structural features at an early stage of the study. This would, of course, have allowed areas for detailed field and photo study to have been more judiciously chosen.

Several image enhancement techniques, including digital and video image processing and color additive viewing were applied to selected pieces of color, color IR and multiband photography and thermal IR imagery. The major goals of image enhancement were (1) detection of linear features, and (2) discrimination of rock types. Although both goals were realized with varying degrees of success, equivalent detection and discrimination could generally be made by inspection of the original imagery data. In addition, machine processing gave equal importance to geologic and non-geologic phenomena alike, a situation avoided by human interpretation on the original imagery data. Image enhancement techniques, for the purpose of this study, were therefore judged impractical due to expense, time, and low "new information" return.

DISCUSSION

Probably the single greatest factor affecting the actual application of remote sensing to this geologic mapping study was the balance between 1) interpretation time and 2) significant geologic information derived from the interpretation. Time constraints forced the investigators to concentrate on the data providing the most information in the shortest interpretation time (i.e.-most useful data). The relative usefulness of the various types of data was determined subjectively by attempting to use the data for geologic mapping (Table I).

TABLE I. RELATIVE USEFULNESS OF REMOTE SENSING DATA USED IN THIS STUDY. NUMBER 1. IS MOST USEFUL, ETC.

1. Low-altitude color photos
2. Low-altitude color IR photos
3. High-altitude color IR photos
4. High-altitude color photos
5. Low sun-angle photos
6. SLAR
7. Multiband photos
8. Thermal IR imagery

Low-altitude color and color IR photography contained the greatest amount of easily extractable geologic information. Low-altitude color photography was judged slightly better than color IR photography because the "natural" color presentation of the photographed scene was generally more useful than the information recorded from the photo IR portion of the spectrum. In some instances, however, geologic features noticed on color photography were enhanced on corresponding color IR photos. For example, linear groves of aspen trees associated with fault-controlled springs were greatly enhanced on color IR photography due to their high reflectivity in the near IR as compared to the conifers in the same immediate area.

High-altitude color and color IR photography is considered the next most useful type of remote sensor data for detailed geologic mapping. Minus-blue filtration (standard in color IR photography) eliminated much of the blue scattering problem caused by the long air path (50,000 feet). The resulting color IR photos are significantly sharper than corresponding color photos and, hence, contain more extractable geologic information in spite of the "false color" presentation.

The remaining types of remote sensor data, with the possible exception of SLAR imagery, were judged impractical or inappropriate for broad-scale general geologic mapping. These data may be useful for solving specific problems in relatively small areas, but acquisition of the data can only be justified if the problem is thoroughly defined beforehand and preliminary studies dictate the need for unconventional remote sensor data. Although not a primary mapping tool, high quality SLAR imagery would probably be desirable for broad-scale geologic mapping programs, particularly in the early stages.

The importance of field investigations concurrent with the interpretation of remote sensor data cannot be overemphasized. Without associated field work, significant interpretative detail was lost and frequent geologic ambiguities developed.

Spot lithologic identification of selected outcrops provided valuable interpretative information. Detailed geologic mapping of relatively small areas within the region was even more productive since geologic interpretations could generally be extended into the surrounding unknown area using remote sensor data. By establishing sufficient field mapping subareas, much of the remaining area could then be mapped accurately and in great detail utilizing the sensor data to tie subareas together.

MAPPING RESULTS

Preliminary analysis of the final geologic map indicates that the mapping program has been successful in delineating the major structural and geomorphic features of the study area (Fig. 5). As suggested by Van Alstine (9), the structure of the

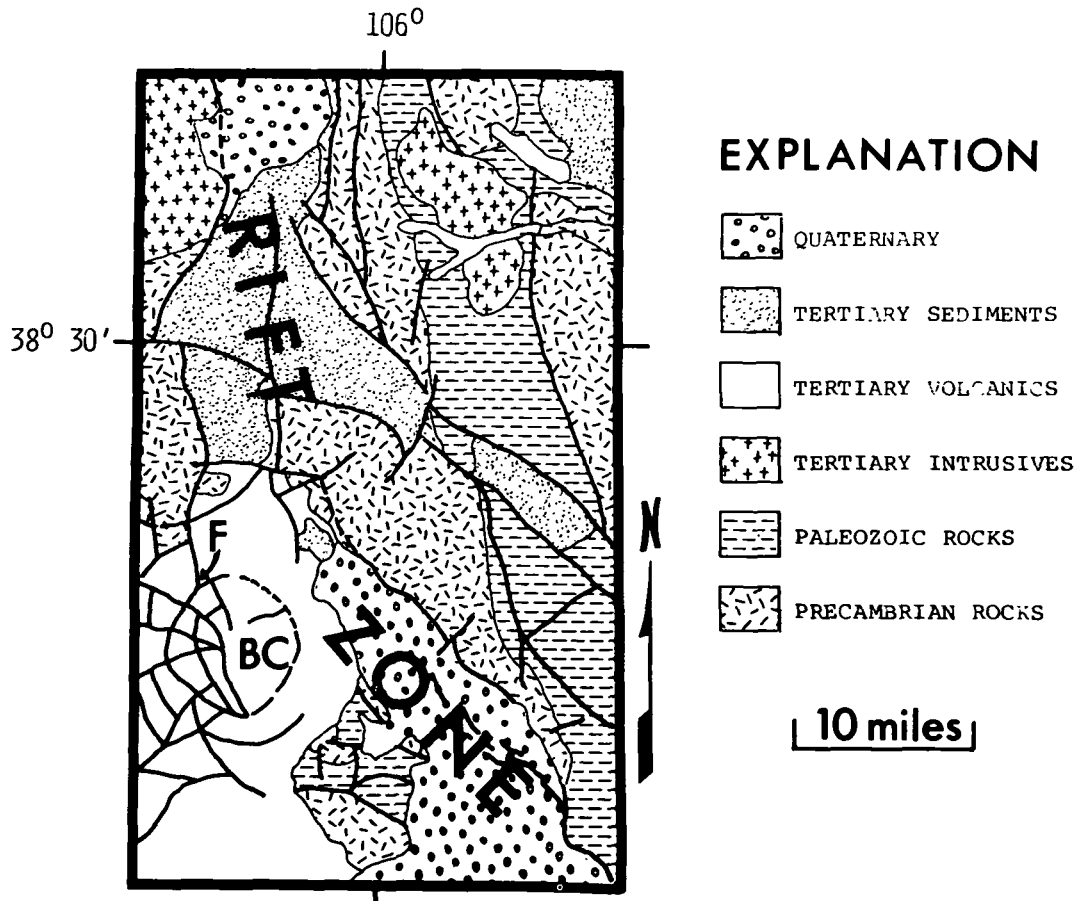


FIGURE 5. GENERALIZED GEOLOGIC MAP OF STUDY AREA.
Western boundary fault of rift zone joins the
Bonanza caldera (BC) ring fault at point F.

Rio Grande rift zone connects the San Luis and Arkansas valleys, although complex transverse faulting commonly disrupts the trend.

In the Arkansas Valley, the internal portion of the rift zone is bounded both on the east and west by major faults. The western boundary fault was traced to the south where it joins the concentric fault system on the western rim of the Bonanza caldera. Most of the presently-observed structural and topographic relief along the western rim of the caldera is due primarily to post-caldera rifting during Miocene and Pliocene time, rather than with caldera formation in the Oligocene. South of the caldera, the rift zone is fault-bounded only on the east side, at the base of

the Sangre de Cristo Range. Most of the present structural and topographic relief of the mountain ranges in the study area (Sawatch, Mosquito, Sangre de Cristo) was produced during the evolution of the Rio Grande rift zone beginning about 25 million years ago, rather than during the Laramide orogeny (50-70 million years ago) as frequently reported. Rifting has continued into the Pleistocene and probably recent times. Faults and fault zones displacing Pleistocene alluvial fans up to 25 feet are remarkably preserved in the San Luis Valley. The preservation of these faults in unconsolidated gravels is suggestive of their youthfulness and has caused some concern over the possibility of future earthquake damage (10); the area has been seismically inactive during historical times.

Geomorphic evolution of the study area began primarily in late Tertiary time with the initial stages of rifting along the Rio Grande rift zone, although widespread volcanic activity in early Tertiary time has certainly left its mark. Streams flowing from the uplifted horst blocks began carving the rugged mountainous terrain and depositing clastic sediments in the graben basins; a through-going stream connected the Arkansas and San Luis valleys. Climatic fluctuations in the Pleistocene produced a sequence of pediment, terrace, and fan deposits marking various stages of geomorphic development. Streams and glacier ice further sculptured the mountains.

SUMMARY

Completion of a detailed geologic map of the study area within the limited amount of time available (3 years) could not have been accomplished without the aid of remote sensor data, particularly the photography. The sensor data provided a means for mapping broad areas rapidly and accurately, and greatly helped to restrict problematical areas to specific sites which could be visited in the field.

The heavy reliance on the application of standard photographic techniques in this investigation is not necessarily indicative of the potential of unconventional photographic and non-photographic data for geologic mapping. Rather, it means that standard aerial photography (color, color IR, panchromatic) is more widely applicable at the present state-of-the-art of practical or operational remote sensing for geologic mapping. The need for continued research and development of remote sensing data acquisition, reduction, and interpretation techniques is very clear -- particularly for the less-common sensors--if the full potential of remote sensing is to be effectively applied to regional geologic mapping.

ACKNOWLEDGEMENTS

This research was supported by the Colorado School of Mines - Bonanza Project under NASA Grant NGL 06-001-015. Over the three-year duration of our studies, the people of the Bonanza Project have always provided a forum in which to air many of our ideas. Professors Keenan Lee and Robert G. Reeves supervised much of the work and contributed many valuable suggestions.

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